

****TITLE****

ASP Conference Series, Vol. ****VOLUME****, ****PUBLICATION YEAR****

****EDITORS****

Thermal Limit Spectroscopy as a Goal for X-ray Astronomy

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Abstract.

The $R \sim 300$ – 1000 grating spectra from XMM-Newton and *Chandra* are a radical advance, allowing spectroscopic physics techniques to be applied to X-ray astronomy, revolutionizing a wide range of research. Ten years on these spectra will be routine, and higher resolution will be needed. I propose “Thermal Limit Spectroscopy” as the next natural goal for X-ray spectroscopy. This will open up new physics: plasma physics, velocity widths, Doppler shifts, line profiles, and absorption lines in photoionized plasmas. A resolution of $R=3000$ – $10,000$ is required, and the technology is within reach.

1. Introduction: the Near Future in X-ray Spectroscopy

The grating spectra from *Chandra* and XMM-Newton are a startling change from the non-dispersive spectra of the earlier era. At a resolution of ~ 300 – ~ 1000 they clearly separate out many the emission lines in soft X-ray spectra for the first time, and allow the application of the physics based techniques of spectroscopy to X-ray astronomy, revolutionizing a vast range of research areas. *Chandra* and XMM-Newton spectra already show that ten years from now we will be in great need of higher resolution spectra.

The next generation of X-ray astronomy missions, ASTRO-E II, Con-X and XEUS, are all primarily spectroscopic, and share the goal of high signal-to-noise, trading better resolution for larger collecting area. All three missions primarily use calorimeters, which should reach ~ 1 – 2 eV resolution by launch (Stahle, these proceedings), i.e. $R \sim 500$ – 1000 at 1 keV, similar to *Chandra* or XMM-Newton. The early *Chandra* HETG spectra in particular, show a great abundance of atomic features below about 1.5 keV, as expected from atomic physics and cosmic abundances, while only the Fe-K line is prominent above ~ 3 keV. So 1 keV (12.54\AA) makes a good reference point for resolution.

How much more resolution do we need? I propose “Thermal Limit Spectroscopy” as the next natural goal of X-ray spectroscopy (Elvis & Fabbiano 1997). The thermal width separates the temperature of the ions (T_{ion} , e.g. O^{5+}) from the electron temperature (T_e); velocity widths, Doppler shifts, line profiles, and absorption lines in photoionized plasmas all then become accessible. A $kT=1$ keV plasma has thermal velocities of ~ 100 km s $^{-1}$, requiring a

resolution of $R=3000-10,000$. The technology for reaching this regime is within reach.

2. A Major Step: Thermal Limit Spectroscopy

The goal of $R \sim 1000$ was driven by a happy combination of scientific goals (resolving the Helium-like triplets) and technological capability (good mirrors and gratings). The next natural goal for X-ray spectroscopy is thermal limit spectroscopy at $R \sim 10,000$, because the next level of physics, as optical and ultraviolet astronomy shows, comes from line profiles. This goal is not technologically absurd. The XMM-Newton RGS gratings would give $R \sim 6500$ if placed behind the $\frac{1}{2}$ arcsec *Chandra* mirrors ¹.

The typical temperature of an X-ray hot plasma emitting at 1 keV is $T \sim 10^7$ K (i.e. $kT=1$ keV, naturally). For a thermal plasma in coronal equilibrium at $T \sim 10^7$ K the typical mid-atomic number (Z) elements such as Oxygen have thermal velocities of $v_{th} \sim 125$ km s⁻¹. (A proton has $v_{th} \sim 500$ km s⁻¹, while an iron atom $v_{th} \sim 75$ km s⁻¹.) A resolution of 3000 thus gives 1 pixel/line width, and a resolution of 10,000 gives a good oversampling of 3 pixels/line width ². Reaching this resolution brings qualitative improvements in the science we can extract from our data, improvements that are not at all restricted to thermal plasmas. I outline some of these below.

More, different lines. A factor of 2 more lines will be separated out of blends at $R=10,000$ vs. $R=300$ (Smith & Brickhouse 2000). More importantly a different type of line becomes resolved at $R=10,000$: dielectronic recombination lines. These are always close to the resonance lines and are always blended at $R=1000$, but can be resolved at $R=10,000$. The dielectronic recombination lines depend only on T_e and ionization, so providing clear new diagnostics.

Thermal Plasma Physics. Normally we assume that cosmic thermal plasmas are equilibrated, i.e. that $T_e = T_{ion}$. Often this is not a good assumption, e.g. any rapidly expanding plasma (solar wind, SNR, galaxy outflows). Testing ion temperatures with line widths ³ vs. T_e is a basic measurement enabled by $R \sim 10,000$. For decades the heating mechanism of the solar corona has been a puzzle. SOHO UVCS has now shown that $T_{ion} > T_e$, ruling out Ohmic heating (for which $T_{ion} < T_e$), and suggesting initial Alfvén heating of the ions (Cranmer 2000). Are all stellar coronae heated this way?

Photoionized Plasmas. Thermal plasmas cooler than $\sim 10^5$ K do not generally produce X-ray lines. Cool *photoionized* plasmas though can show X-ray transitions at all temperatures. Cool material commonly surrounds X-ray sources:

¹ Albeit with a new mounting scheme. The present grating mounts were designed to work with the XMM-Newton mirrors, and so are not controlled to a level that would let their inherent resolution show. According to the RGS designers this is not a major engineering challenge.

² The natural, uncertainty principle, line width $\gamma = \hbar A$ (where A is the Einstein A coefficient), is almost always 0.001-0.1 eV, at most comparable with the thermal width in X-ray hot plasmas, since $10^{12} < A < 10^{14}$ s⁻¹.

³ $\propto Z^{-\frac{1}{2}}$, c.f. constant width for turbulence

X-ray binaries, HII regions and AGN are all rich in cool gas. Measuring these lines will tell us about the flows of this gas, and hence dynamics and mass loss rates, and can delimit the often unseen ionizing continuum. Radiatively driven winds, (e.g. P Cygni) are unstable and typically break up, producing many narrow absorption features. While narrow emission lines are easily detected, an absorption line from 10^4K gas (thermal width $\sim 10\text{ km s}^{-1}$) needs $R \sim 15,000$.

Doppler Motions. The Doppler effect is one of the most employed methods for understanding astronomical objects. In highly ionized matter around X-ray sources optical or ultraviolet lines are weak, while X-ray transitions dominate. Systems with velocities $\sim 1000\text{ km s}^{-1}$ are open to *Chandra* and XMM-Newton. Most Doppler velocities are over an order of magnitude smaller: e.g. G-star winds, where *Doppler tomography* via rotation can map coronal structures, have $\Delta v \sim 10\text{ km s}^{-1}$; X-ray binaries have orbital velocities $v \sim 300\text{ km s}^{-1}$; the hot ISM can map Galactic structure over a range $v \sim 0\text{--}300\text{ km s}^{-1}$; AGN absorbers have $\Delta v \sim 30\text{ km s}^{-1}$; and cluster mergers take place at the sound speed $v \sim 300\text{ km s}^{-1}$. To measure line centroids to $\sim 20\text{ km s}^{-1}$ needs a FWHM $< 200\text{ km s}^{-1}$, i.e. $R > 3000$.

Photoabsorption Edge Resonances & Dust. The dust-to-gas ratio is key to many astrophysical situations (e.g. planet formation), but is surprisingly hard to measure. X-ray edge structures (e.g. McLaughlin & Kirby 1998) depend on the molecular state of the atoms. e.g. Is oxygen is atomic, O_2 , CO_2 , or in a silicate dust particle such as MgSiO_3 . Ferric ISM dust grains have been found this way with *Chandra* (Paerels et al., 2001). Many edge structures require $R > 1000$.

The Killer App: The Missing Baryons. While compelling science, none of the above is readily condensed into a sound bite that can capture public attention. One application could do: the study of the ‘missing baryons’. At low z most ‘normal’ matter should be hidden in a warm-hot ($10^6\text{K--}10^7\text{K}$) intergalactic medium studiable only in soft X-rays (Fiore, these proceedings). *Chandra* will probably give the first detection of this medium. Detailed study though - are they thermal or photoionized, engaged in large scale motions, polluted by galaxy superwinds - requires resolving line widths and looking for small Doppler shifts, for many ions. This requires thermal limit X-ray spectroscopy.

3. Achieving Thermal Limit Spectroscopy

Even if thermal limit spectroscopy is an obvious goal for X-ray astronomy, it will not be accepted as the right next step if the technology is too far from realization. Luckily, both mirrors and spectrometers are surprisingly close to the needed performance.

Mirror Size. The power of any telescope depends on ‘ $fA\epsilon$ ’. The product of flux, area, exposure time and efficiency, when divided by the mean photon energy, determines the number of photons collected. At high resolution emission lines need only slightly greater mirror area, since they will simply show up more clearly against a zero continuum value until resolved. Narrow absorption lines need a minimum of 10 continuum counts per bin to be detected significantly. At $R=5000$ this requires 1 sq.meters effective area for a source at $2 \times 10^{-12}\text{erg cm}^{-2}\text{ s}^{-1}$ (i.e. ~ 3000 targets in the sky) in 10^4s . This is comparable to Con-X and smaller than XEUS-I.

Spectrometers.

Calorimeters combine high efficiency with a broad band and ‘integral field’ spectroscopy (i.e. a spectrum at every image pixel). However the thermal noise requires that such a calorimeter operate at ~ 5 mK, vs. ~ 50 mK for today’s instruments, but other noise sources may prevent its realization.

Bragg Crystals naturally reach $R \sim 1000$ and have an intrinsically broad field of view. However they have narrow ($\sim 1\%$) band passes and so a low efficiency if many lines are needed. Reaching $R \sim 10,000$ is not easy.

Transmission Gratings are lightweight and cover a large bandwidth. They have $\epsilon=0.3$, vs. $\epsilon \sim 1$ for calorimeters, but this is small factor compared with the increase in mirror area needed in any case. Transmission grating periods of 80\AA , 5 times smaller than on the *Chandra* MEG at 1 keV, are now feasible (Savas et al 1996), resulting in $R \sim 5000$ behind a *Chandra*-like mirror. Extended sources are non-trivial however. ‘Long-slit’ designs, as in optical astronomy, could overcome this problem, at the cost of doubling the length of the optics system. This may no longer be a significant constraint now that station keeping (e.g. XEUS) is needed. Transmission gratings require a high resolution mirror, improving R as the mirror improves. Such mirrors are needed in any case for imaging applications (Fabbiano, these proceedings).

Reflection Gratings can already provide resolutions of the right order, given a ~ 1 arcsecond mirror. Again extended sources would require ‘long slit’ optics. ‘Out of plane’ geometries (Cash 1991) offer higher spectral resolution, and higher efficiency. With $5''$ HEW mirrors Con-X could achieve $R=5000$ (Cash 2001).

4. Conclusion

Cosmic X-ray spectroscopy is a new field. At last the techniques of atomic physics are being applied to astronomical X-ray sources. With $R \sim 1000$ there are wonderful riches, but a decade from now will that be enough? The promise of $R \sim 10,000$ resolution is technologically not too distant. Thermal limit X-ray spectroscopy is the right choice of goal for a new generation of X-ray missions.

This work was supported in part by NASA grant NAG5-6078.

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